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Paleo-Tsushima Water influx to the East Sea during the lowest sea level of the late Quaternary

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Abstract: The East Sea, a semi-enclosed marginal sea with shallow straits in the northwest Pacific, is marked by the nearly geographic isolation and the low sea surface salinity during the last glacial maximum (LGM). The East Sea might have the only connection to the open ocean through the Korea Strait with a sill depth of 130 m, allowing the paleo-Tsushima Water to enter the sea during the LGM. The low paleosalinity associated with abnormally light $\delta^{18}O$ values of planktonic foraminifera is interpreted to have resulted from river discharge and precipitation. Nevertheless, two LGM features in the East Sea are disputable. This study attempts to estimate volume transport of the paleo-Tsushima Water via the Korea Strait and further examines its effect on the low sea surface salinity (SSS) during the lowest sea level of the LGM. The East Sea was not completely isolated, but partially linked to the northern East China Sea through the Korea Strait during the LGM. The volume transport of the paleo-Tsushima Water during the LGM is calculated approximately $(0.5\text{-}2.1)\times10^{12}$ m^3/yr on the basis of the selected seismic reflection profiles along with bathymetry and current data. The annual influx of the paleo-Tsushima Water is low, compared to the 100 m-thick surface water volume (about 79.75×10^{12} m^3) in the East Sea. The paleo-Tsushima Water influx might have changed the surface water properties within a geologically short time, potentially decreasing sea surface salinity. However, the effect of volume transport on the low sea surface salinity essentially depends on freshwater amounts within the paleo-Tsushima Water and excessive evaporation during the glacial lowstands of sea level. Even though the paleo-Tsushima Water is assumed to have been entirely freshwater at that time period, it would annually reduce only about 1‰ of salinity in the surface water of the East Sea. Thus, the paleo-Tsushima Water influx itself might not be large enough to significantly reduce the paleosalinity of about 100 m-thick surface layer during the LGM. This further suggests contribution of additional river discharges from nearby fluvial systems (e.g. the Amur River) to freshen the surface water.

Keywords: the East Sea, last glacial maximum, sea-level changes, paleoceanography, paleoclimates

Introduction

A semi-enclosed marginal sea with shallow and narrow sills is vulnerable to sea-level variations. Such a marginal sea tends to preserve paleo-records for the fluctuating sea levels that are especially related to the late Quaternary glacial and interglacial periods. The last glacial maximum (LGM) is a time interval of the lowest sea level in the last glacial period. A decreased sea level at that time period made a large part of the shallow sea exposed, establishing a land bridge and then separating the sea from the adjacent marine settings. Subaerial exposure of shallow-water regimes has been briefly presented near the eastern Siberia, the Alaska and the southeastern Asia while partial connections to nearby open seas were also recognized in the Mediterranean Sea and the Red Sea during the sea-level lowstand of the LGM (Zhuo et al., 1998; Petit-Maire et al., 2000).

The East Sea, a typical marginal sea between the Northeast Asia and Japanese islands, is approximately 1,000,000 km^2, and its mean depth is 1350 m with a maximum depth of 3,700 m. The sea is linked to the South Sea of the Korea through the Korea (Tsushima) Strait (140 m in sill depth), to the northwest Pacific Ocean through the Tsugaru Strait (about 130 m), and to the Okhotsk Sea through the

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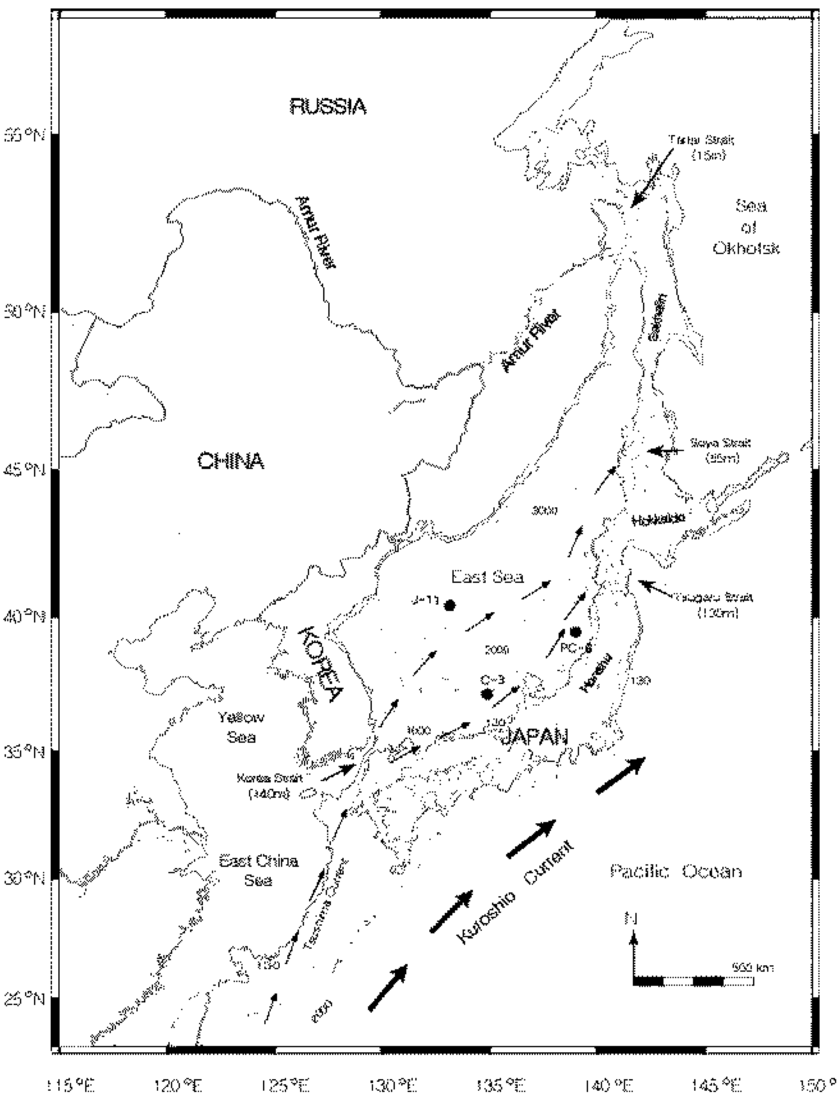

Fig. 1. The East Sea is presently surrounded with landmass and islands with four shallow straits (the Korea, the Tsugaru, the Soya, and the Tartar). The Tsushima Current predominates in surface layer of the sea, entering through the Korea Strait and exiting mostly through the Tsugaru and Soya straits. The light gray area indicates exposed shelf during the last glacial maximum. Solid circles are core locations (C-3, J-11 and PC-9) from previous studies (Oba et al., 1991, 1995; Gorbarenko and Southon, 2000; Ishiwatari et al., 2001). Bathymetry is in meters.

Soya (55 m) and Tartar (15 m) straits (Fig. 1). This sea also has structural highs (the Korea Plateau and the Yamato Rise) with less than 1,500 m and lows (the Ulleung, the Yamato and the Japan basins) with deeper than 2,000 m. The East Sea is vertically stratified in two layers: surface water and deep water. The surface water is well-mixed, and dominated by the warm Tsushima Current and cold Liman Current. The Tsushima Current flows into the East Sea via the Korea Strait supplying salt and heat energy, and then flows out the sea mostly through the Tsugaru and Soya straits (Toba et al., 1982; Lim and An, 1985; Isobe, 1999). This warm current usually transports the saline water (1~2 Sv) to the East Sea, with the velocities ranging from 10 to 80 cm/sec (Lee and Jung, 1977; Toba et al., 1982; Korea Hydrographic Office, 1982; Ichiye, 1984; Lim and An, 1985; Isobe et al., 1994; Isobe, 1999). The Tsushima Current is generally faster in summer than in winter (Lee and Jung, 1977; Korea Hydrographic Office, 1982; Ichiye, 1984; Isobe et al., 1994). Temperatures of the Tsushima Current average about 26°C in summer and 14°C in winter (Toba et al., 1982; Lim and An, 1985). On the other hand, the deep water named as the East Sea Proper Water (ESPW) is cold (0~1°C) and well-oxygenated (Itaki et al., 2004; Kang et al., 2004). This water is subdivided into 3 water masses: the East Sea Central Water (ESCW), the East Sea Deep Water (ESDW) and the East Sea Bottom Water (ESBW) (Kang et al., 2004). The cold deep water is thought to originate from the northwestern East Sea because of strong cooling of surface water and sea ice formation during winter (Nitani, 1972; Gamo et al., 1986; Martine et al., 1992).

Indeed, the East Sea with the shallow straits must have experienced global sea-level oscillations associated with the repeated glacials and interglacials in the late Quaternary. Peculiarly during the interval of the LGM, the globally lowered sea level resulted in the emergence of the shallow straits, developing the land bridges at the Tsugaru, the Soya and the Tartar straits. On the contrary, the Korea Strait with the deepest sill was partially open although it was shoaled by glacioeustatic sea-level drop. Subsequently, the geomorphologic modification might have altered volume transport via the Korea Strait, surface water properties, vertical mixing between surface and deep, and depositional patterns in the East Sea. In particular, the LGM East Sea has been marked by the low sea surface salinity of about 20‰ (Tada, 1999) associated with abnormally light δ^{18}O of planktonic foraminifera (Oba et al., 1991; Gorbarenko and Southon, 2000) which is opposite to the globally positive values at this period. The low SSS and the relevant isotopic excursion shown in Fig. 2 seem to have been caused by freshwater dilution through the river runoff and precipitation (Oba et al., 1991; Keigwin and Gorbarenko, 1992; Tada et al., 1999; Gorbarenko and Southon, 2000; Lee and Nam, 2003). However, the geographic isolation and low paleosalinity in the LGM East Sea still remain on debate.

This paper primarily focuses on paleoceanographic changes of the East Sea triggered by the LGM sea-level fall, as mentioned above. In this study two aspects are examined: (1) the opening and the volume transport at the Korea Strait during the LGM, (2) the low sea surface paleosalinity event and its major causes. For this study, the selected seismic reflection profiles have been analyzed to estimate the cross-sectional area at the paleo-Korea Strait. Additionally, previous studies have been critically reviewed.

Background

It is generally well-known that the LGM ranging from 23 to 19 calendar (cal) ka BP (Mix et al., 2001) is one of the most striking climatic events in the late Quaternary. The LGM interval referred to as the Marine Isotope Stage (MIS) 2 is characterized by cold, dry and windy climate, along with a maximal 130 m drop of sea level (Fairbanks, 1989; Yokoyama et al., 2000; Ruddiman, 2001). Usually, this glacial world was about 4 colder than the present Holocene interglacial climate (CLIMAP members, 1981). The overall LGM features are likely to have synchronously occurred around the Korea seas. For instance, the Korean Peninsula and the Taiwan Island were connected to the mainland China during the LGM (Zhuo et al., 1998; Yasuda et al., 2004). The Yellow Sea disappeared, and the South Sea was nearly exposed to the air. As a result, the coastline of the East China had shifted by 600~1,000 km eastwards from its present position (Wang and Wang, 1980; An et al., 1991), and then the Yellow River mouth migrated around Cheju Island (Oba et al., 1991; Zhuo et al., 1998; Tada, 1999).

The East Sea climate must have been deteriorated during the LGM (Yasuda, 1984; Morley et al., 1986; Oba et al., 1991; Gorbarenko and Southon, 2000). The sea surface temperature (SST) around the East Sea decreased by about 4~6°C during the LGM (CLIMAP members, 1981; Kim et al., 2003). However, the surface area of the East Sea at that time period would largely maintained its own extent, covering approximately 85% of the present surface area, because the sea is much steeper and deeper than the Yellow and the South seas. The closure of three shallow straits (the Tsugaru, the Soya and the Tartar) as noted earlier has been postulated in response to the LGM drop in sea level (Yasuda, 1984; Oba et al., 1991; Keigwin and Gorbarenko, 1992; Matsui et al., 1998; Tada, 1999; Kim et al., 2000; Park et al., 2000). Actually, Kuzmin et al. (2002) revealed human exchange and migration from the northeastern Asia through the Sakhalin to the Hokkaido at least since 23,000 cal. yr BP. This proves the land bridge establishment at the Tartar and the Soya straits. The land route to the Honshu has been also suggested since 30,000 yr BP (Oda, 1990; Motohashi, 1996), indicating the emergence of the Tsugaru Strait. Additionally, the pre-exposure of the Tsugaru Strait has been investigated with a measurement of ^{10}Be concentration for underwater rock samples during the sea-level lowstands of last glacial period (Kim and Imamura, 2004).

Partial Opening of the Korea Strait

Complete closure of the Korea Strait during the LGM has been propounded, blocking the paleo-Tsushima Current influx into the East Sea (Yasuda, 1984; Ono and Naruse, 1997; Kim et al., 2000; Ono et al., 2004). Otherwise, the East Sea might not be entirely isolated from the northern East China Sea (Keigwin and Gorbarenko, 1992; Matsui et al., 1998; Tada, 1999; Tada et al., 1999; Park et al., 2000; Ishiwatari et al., 2001; Lee and Nam, 2003).

Particularly, Oba et al. (1991) argued in favor of the Korea Strait closing during the LGM. They also added that freshwaters from the Chinese fluvial system were released in the vicinity of the Cheju Island due to the southward shift of the Yellow River mouth, ultimately spreading into the East Sea. If, however, the hypothesis by Oba et al. (1991) is correct, the Korea Strait would be at least partially open during the LGM, allowing a persistent but limited influx of the paleo-Tsushima Current, together with freshwaters. According to Keigwin and Gorbarenko (1992), the paleo-Korea Strait was 15 km wide, but it did not virtually play a significant role in lowering the SSS in the East Sea during the LGM. Comparatively, the channel-like strait has been proposed during the LGM lowstand of sea level, further indicating a continuous inflow of the paleo-Tsushima Current and its influence on the low SSS (Matsui et al., 1998; Park et al., 2000). In addition, the warm-water diatoms and the low-salinity diatom (*Paralia sulcata*) were identified in core sediments (Morley et al., 1986; Park et al., 2000) from the southern East Sea, suggesting the inflow of both the Tsushima Current and the East China Sea coastal waters through the paleo-Korea Strait (Koizumi, 1989; Tada, 1999; Tada et al., 1999). Recently, Lee and Nam (2003) remarked that the western part of the Korea Strait was partially inundated during the LGM, through which freshwater from the nearby fluvial systems (Nakdong and Seomjin rivers) entered the East Sea, presumably affecting surface salinity condition.

Interestingly, Ishiwatari et al. (2001) discovered much higher sea surface temperatures (about 18°C) during the LGM when the East Sea was strongly stratified due to limited vertical mixing between surface layer and deep water (Fig. 2). They also interpreted that the higher surface temperatures than previously estimated values might have been generated by thermal energy trapped in surface waters. However, it can not be ruled out that the warm Tsushima Current continuously penetrated into the East Sea (via the paleo-Korea Strait), supplying

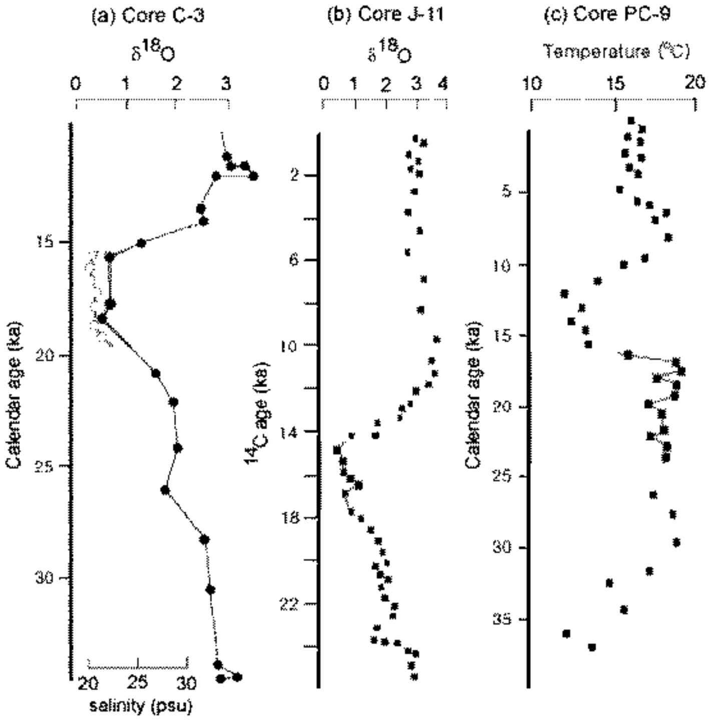

Fig. 2. Downcore variations in $\delta^{18}O$ of planktonic foraminifera, salinity and sea surface temperatures. (a) $\delta^{18}O$ (Oba et al., 1995) and salinity (Tada, 1999) are extracted from Core C-3 with cal. calendar ages. Open circles for salinity, displaying the lowest value (down to 20‰) between 15 and 20 cal. ka BP. Closed ones for $\delta^{18}O$. (b) $\delta^{18}O$ trends are based on Core J-11 with ^{14}C age dates (Gorbarenko and Southon, 2000). (c) The sea surface temperatures reproduced by the analyses of alkenones, showing high temperatures between 17 and 24 cal. ka BP than expected (Ishiwatari et al., 2001). The shaded areas indicate the time intervals of low surface paleosalinity associated with light $\delta^{18}O$ and high surface temperatures with different chronological determinations.

heat energy to the sea. The ensuing high surface temperatures together with freshwater input might have a consequential influence on the light $\delta^{18}O$ records of planktonic foraminifera. Therefore, the comprehensive review of previous studies strongly supports that the Korea Strait was partially open as a very narrow channel, transporting both the paleo-Tsushima Current and freshwater (hereafter, "the paleo-Tsushima Water") to the East Sea at the maximal peak of the last glacial period.

Paleo-Tsushima Water Influxes

In this study, the paleo-Tsushima Water amounts passing through the Korea Strait during the LGM have been estimated, based on bathymetry, seismic reflection profiles and the present current data. A cross-sectional area at the paleo-Korea Strait has been assessed about 10 km wide and 10 m deep, which is almost similar to its extent previously assumed by Matsui et al. (1998). To obtain the accurate paleo-depth in the Korea Strait region, sediment layer deposited since the LGM is averaged by about 7 m in thickness, extracted from the analyses of selected seismic reflection profiles (Fig. 3). The corrected cross-sectional area of the paleo-Korea Strait is approximately 170,000 m^2 by multiplication of 10 km wide and 17 m deep.

The present current velocities (varying from 10 to 80 cm/sec at the Korea Strait) have been used to infer the paleo-Tsushima Water speed because the paleo-current velocity can not be directly measured.

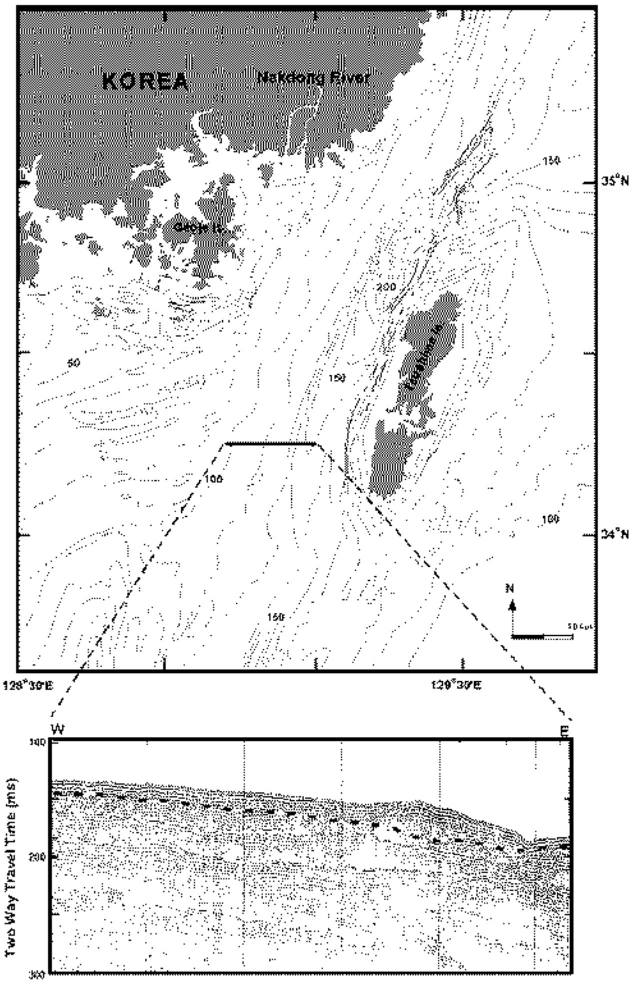

Fig. 3. The Korea Strait shelf region, displaying the general bathymetry. Solid line indicates the site for seismic profile acquisition by a Sparker. About 5~10 m of sediment layer (above the dotted line) is interpreted to have accumulated since the LGM. The sediment thickness is estimated on the basis of the seismic velocity of about 1500 cm/sec measured in Pleistocene sediments.

The main path of the Kuroshio Current during the LGM turned southward (CLIMAP members, 1981; Ujiie and Ujiie, 1999) because extension of the Kuroshio Current to the northern East China Sea might be considerably restricted owing to the land bridge formation around Taiwan and the Ryukyu islands (Ujiie et al., 1991; Ahagon et al., 1993). Afterward, the Tsushima Current, a branch of the Kuroshio Current, weakened at that time period. For this reason, the present lower values (10~40 cm/sec) were taken as the paleo-current velocities. Finally, the volume transport at the paleo-Korea Strait is calculated about $(0.5\sim2.1)\times10^{12}$ m^3/yr by the multiplication of the cross-sectional area and the inferred current velocity.

Low Paleosalinity Event

It has been already mentioned that the low SSS in the East Sea during the LGM would closely relate to the unusually light δ^{18}O values of the planktonic foraminifera. This points out that local effect strongly modified the isotopic composition of the surface water for the LGM. Tada (1999) reconstructed that surface salinity in the LGM East Sea noticeably decreased down to 20‰, using the oxygen isotope data (Oba et al., 1991, 1995). This paleosalinity is about 14‰ lower than the present value (34‰). The low SSS phenomenon has been attributed to the freshening by high precipitation (Keigwin and Gorbarenko, 1992; Tada, 1999; Gorbarenko and Southon, 2000), and/or by river discharges from adjacent land (Oba et al., 1991; Tada et al., 1999; Gorbarenko and Southon, 2000; Lee and Nam, 2003).

Surface Evaporation

The East Sea was colder, windier and drier during the glacial periods. The downcore variations of aeolian dusts have been examined in core sediments deposited in the late Quaternary (Irino and Tada, 2002). The aeolian dust content derived from both the Chinese mainland and the Japanese islands increased during the LGM. These high accumulation rates are interpreted to have resulted from the eastward advance of the source area due to the exposure of the Yellow Sea and from the lateral transport of suspended particles from the Japan Arc, respectively. This further reflects that stronger wind served as an essential transport agent for aeolian material during glacial period when precipitation was low. In fact, sediment discharge through the Yellow River was greatly decreased due to a decreased precipitation during the LGM (Saito, 1998). Moreover, low precipitation appears to have prevailed in the Japan during this time period (Yasuda, 1987). The simulation results (Kim et al., 2003) display that sea surface temperatures around the Japanese islands were lowered by about 6°C during the LGM. This is an indicative of the decreased precipitation in the East Sea because temperature depression usually causes precipitation reduction. Earlier climate modeling data also provided that surface evaporation around the East Sea have exceeded precipitation, showing about 1-3 mm/day of net evaporation (evaporation minus precipitation) during the LGM (Rind and Peteet, 1985; Crowley and North, 1991; Wright et al., 1993). If the net evaporation values are used for the East Sea during the LGM, the surface evaporation rates would be roughly about (0.3-0.9×10^{-2} m^3/yr), based on the previously simulated results (1-3 mm/day) and the corrected surface area (0.85×10^6 km^2). Modern climate data report that annual mean evaporation (3.27 mm/day) is higher than precipitation (2.96 mm/day) in the East Sea (Yanagi, 2002). The higher evaporation pattern seems to be maintained in the East Sea during both the interglacial Holocene and the LGM.

All these studies reliably support that the East Sea would undergo stronger wind and lower precipitation during the LGM. It is deduced that evaporation would have been higher than precipitation during the LGM. Thus, precipitation suggested in previous studies might not be such a critical factor to decrease sea surface salinity over the LGM East Sea.

River runoff

There are two sources of river water responsible for the low paleosalinity at the time of the LGM; the Chinese freshwaters largely from the Yellow River (Oba et al., 1991; Tada, 1999), and, to some extent, Korean fluvial waters from the Nakdong and the Seomjin rivers (Lee and Nam, 2003). It is generally accepted that the freshwaters as an important component of the paleo-Tsushima Water were carried into the East Sea only through the Korea Strait during the LGM. However, it is not yet known how much the paleo-Tsushima Water retains freshwater, further influencing paleosalinity of the surface water.

Here, the effects of the paleo-Tsushima Water on the paleosalinity are discussed with some assumptions. The present surface layer in the East Sea is presumed to lie between sea surface and down to 100 m since planktonic foraminifera mostly dwell within these depth ranges (Haq and Boersma, 1978). The surface layer during the LGM is situated from −130 to −230 m in present depths. So, the surface

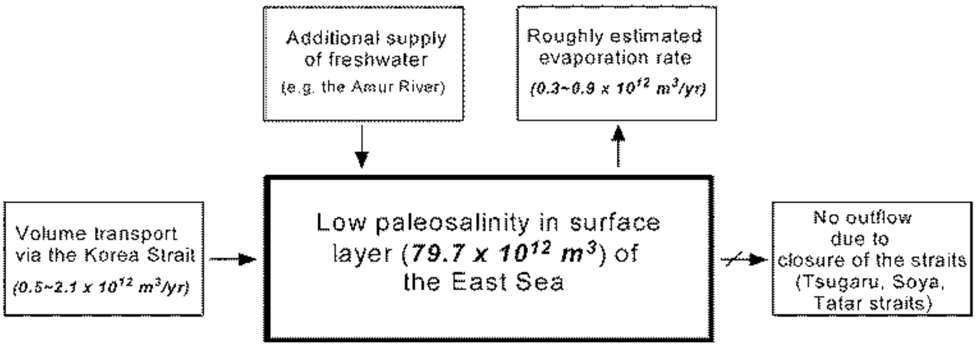

Fig. 4. A schematic diagram illustrates the surface water budget of the East Sea during the LGM. The surface paleosalinity seems to have been influenced by freshwater amount within the paleo-Tsushima Water and excessive evaporation. If the paleo-Water is entirely non-saline, it could only decrease less than 1‰ of the sea surface salinity. Thus, this indicates additional freshwater supply to decrease the sea surface salinity, presumably by the Amur River discharge and adjacent fluvial systems.

water volume is assessed about 79.75×10^{12} m^3 at that time. If the SSS was about 20‰ during the LGM (Tada, 1999), the surface water would be composed of water (78.16×10^{12} m^3) and salt (1.59×10^{12} m^3). Simply, the freshwater amounts (78.16×10^{12} m^3) in the East Sea surface layer is much higher than the volume transport ($0.5 \sim 2.1 \times 10^{12}$ m^3/yr) at the paleo-Korea Strait (Fig. 4). Even though the paleo-Tsushima Water is assumed to have been entire freshwater during the LGM, it would annually reduce only about 1‰ of salinity within the 100 m-thick surface layer of the East Sea. Seemingly, the comparison between the volume transport and surface water volume implies that the former could change surface water properties within geologically short term, affecting sea surface salinity.

At this point, two aspects should be considered. Primarily, the paleo-Tsushima Water is not 100% freshwater. The effect of the volume transport on the low SSS essentially depends on how much the paleo-Tsushima Water contain freshwater during the glacial lowstands of sea level. Secondly, the higher evaporation might play a potential role in the increase of the SSS during the LGM. Lee and Nam (2004) denote that even though the paleo-Tsushima Water is the only freshwater, its amounts might not be sufficient to explain the low SSS on the basis of review on the relationship between the salinity and δ^{18}O (Broecker, 1989). Therefore, the paleo-Tsushima Water influx only through the Korea Strait into the East Sea is not large enough to verify the low paleosalinity event. This further suggests additional freshwater input to the East Sea during the LGM (Fig. 4).

Kim et al. (2003) simulates that freshwater discharge by the Amur River increased by about 80% during the LGM, while the Yangtze River discharge decreased by 25% during that time period. This implies that the Amur River could be an additional freshwater source to the northern East Sea during the LGM. Probably, the southward invasion of the Amur River discharge might be faced with sea ice coverage in the northern East Sea during the LGM. The maximal expansion of sea ice seems to have been delimited to the northern East Sea during the LGM, presumably in the southern Hokkaido (Ono, 1984; Ikehara et al., 2003). Even though sea ice coverage expanded to the northern part of the sea, freshwater would flow into the sea beneath coastal sea ice. For this reason, sea ice expansion could not detain southward intrusion of the Amur River during the LGM. This paper, therefore, strongly suggests that the Amur River could be an important source for freshwaters, but its contribution to the low SSS has not been clarified yet. Additionally, freshwater input from the east coast of

Korea and from the Japan needs to be further studied to understand the low paleosalinity of the East Sea since the river runoff not passing through the paleo-Korea Strait has been ignored, especially in the field of climatic modeling.

Concluding Remarks

The LGM paleoceanographic changes of the semi-enclosed East Sea are basically dependent on the sill depths in response to the globally lowered sea level. The Korea Strait was shoaled, but still existed as a narrow channel, allowing a rather limited influx of the paleo-Tsushima Water (the mixture of the paleo-Tsushima Current and freshwaters) to the sea during the LGM.

The volume transport $(0.5\text{-}2.1 \times 10^{-2}\ \mathrm{m^3/yr})$ at the paleo-Korea Strait may, to a certain extent, affect the lowering of sea surface salinity. However, its effect on the low SSS is subject to freshwater amounts within the paleo-Tsushima Water and excessive surface evaporation. The paleo-Tsushima Water influx might not be large enough to significantly dilute surface water during the lowest sea level of the LGM. Subsequently, additional river runoff (e.g. the Amur River) is suggested to justify the low paleosalinity event during the LGM.

This study also leaves further detailed investigations. It has not been clearly determined that the timings of the lowest sea level and the low SSS are concurrent during the LGM. These paleo-events in the MIS 2 can be compared with those in MIS 6 when sea level was low, too. High-resolution climatic simulation for the East Sea deserves to be conducted for better understanding of the regional LGM conditions, further correlating to geological proxies extracted from sediment sequences.

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